STEADY STATE SOUND PRODUCTION AND INVESTIGATIONS ON CLASICAL GUITARS

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1. ABSTRACT

The discussion about the quality of a guitar goes back to the early days of this instrument. Due to its growing popularity in the last decades numerous experiments and theoretical investigations have been published in order to better understand the instrument and to improve the quality of the tone production.
The possibilities and tools to investigate the functionality and properties of a guitar have developed dramatically in recent years due to the application of fast and cheap computers. Mathematical procedures and modelling with finite element methods allow to simulating any instrument.
Here, a more practical approach is presented. The guitar is slightly modified to produce the sound in the very same way the string tension acts on the bridge. The guitar under test is agitated with steady state signals or, for range measurements, as sweep-sine or MLS (Maximum Length Sequence) signals.
With such defined steady state signals, analysis is by far more easier to accomplish.
Shown are frequency response measurements on famous old guitars and new models, the influence of string tension and weight distribution, temperature and humidity. All results are verified by conventional measuring methods.

2. INTRODUCTION

The discussion about the quality of a guitar has a long history. Recently, however, the instrument has gained much popularity, presumably because many think it is not difficult to learn. By no means, it is! My teacher tends to claim that it is by far the most difficult instrument! Neither is it an instrument easy to investigate: it has a complex structure, non steady state tone production, and large design variations. Due to its growing popularity in the last decades numerous experiments and theoretical investigations have been published in order to better understand its physics and improve the quality of tone production.
Vibration analysis and modal investigations are common to most engineers in design and development today. They look into vibration behaviour of washing machines, jumbo jets, and skyscrapers. These procedures are used to optimising properties and minimising potential dangers and failures.
These tools can easily be applied to musical instruments. For such investigations, analytical procedures and numerical calculations are cast into easy to handle programs.

Here, we describe a new procedure applied to guitars of various origins and age. Extensive and comparative measurements allow showing differences throughout the whole audio spectrum. The interpretations of these results are presented for discussion.

3. RECENT LITERATURE

Many publications are available on single aspects of the guitar. A concise presentation of the properties was published in 1985 [1]. Systematic measurements and conclusive analysis show the influence of many parameters of the guitar and may be used as guidance for luthiers. A simple correlation between physical parameters and the sound quality is, however, difficult, maybe impossible. Therefore, an audio evaluation of different guitars by experts is added for orientation. A collection of methods and measurements was presented 2010 on several string instruments. Quality criteria are suggested, bases on statistical methods [38].
Modal analysis using laser vibrometers and other optical methods show the various oscillating modes of the guitar body [2]–[16], [40]. The analysis requires defined excitation parameters. If the agitation forces are unknown, operational modal analysis (OMA) is also possible, but it requires many measuring points to isolate modes from noisy signals. Nevertheless, modal behaviour does not necessarily relate to the quality of a guitar.

Finite element methods were applied to the guitar models to simulate vibration modes or isolate critical parts and to investigate their influence on the sound performance [25], [26], [37]. Two severe problems are encountered, however:
1st, wood is an un-isotropic matter in terms of physical and mechanical properties. They vary with time and space.
2nd, tone production on the guitar is a non-steady state process and therefore requires small increments in time and space. This asks for extensive computer power and speed.

Numerous investigations present measurements on the input admittance, impedance or transfer function using piezoelectric transducers [7], [10], [18], [27]. These measurements provide a good insight of the ability of the instrument body or parts of it to oscillate, when the string is released. The visualisation of the soundboard movements [40] is also a proper tool to reveal to the luthier “lazy” parts of the soundboard. The artist, however, wants to hear the sound of a guitar. He wants to find out, if the tone production suits his imagination and taste and if the tone can be formed at his will.
Therefore, the straightforward analysis is to investigate the transfer function between agitation and sound radiation by using a professional microphone.

4. SEADY STATE TONE PRODUCTION

To apply home computer based tools, a steady state signal from the guitar is desirable. Studying and understanding the mechanism of tone production with a guitar shows, that the oscillating sting rocks the bridge not only by transversal forces, but also by longitudinal forces. This longitudinal force results from the string displacement causing a variation in longitudinal tension. The longitudinal forces are smaller than the transvers forces according to calculations by Fletcher [40]. Nevertheless, they rock the bridge resulting in tilting movements. We replace the bridge inlay (fishbone/ivory) by a brass inlay having a lever arm on the bass string side. The lever arm extends vertical to the soundboard and is connected to an electromagnetic shaker. The

shaker is fed with an electric signal. This agitation gives a steady state tone at any desired frequency and sound level by changing the frequency and output level of the driving generator.

5. THE TEST FACILITIES

The experimental set-up is designed in such a way, that the sound production is reproducible under all circumstances. The apparatus itself shall not vibrate in the audio frequency range and shall not hinder the guitar to vibrate and respond to agitating forces applied. The guitar under test is ready to be played. All strings are mounted and tuned, so the soundboard of the guitar is under operational tension. The strings, however, are damped with a noun strip. The string vibrations do not contribute to the sound measured by a calibrated microphone.
The guitar body is mounted vertically on a very rigid aluminium structure of one pillar and two arms. Four wooden brackets fix the guitar body at the back and front.
Little force is applied to the guitar at the very edge of the soundboard and back plate. At the lower end of the guitar body the shaker (Brüel & Kjaer 4810) is placed on an aluminium table extending from the main pillar structure. The piston of the shaker is connected to the lever arm made from a carbon fibre tube. This tube is very rigid and has a low mass. The shaker can be moved horizontally, so no momentum is applied to the lever arm when the shaker is unpowered. An extra mass of 900 grams is added to the bottom of the shaker to lower resonant frequencies.

6. AGITATION OF THE GUITAR AND MEASURING DEVICES

The shaker is fed with a sine wave signal, a white or pink noise signal from a signal generator (Brüel & Kjaer 1049), or by audio signals produced by the computer. A linear amplifier (Brüel & Kjaer 2706) gives enough power to drive the shaker. The sound radiated from the guitar is received by a condenser microphone (Brüel & Kjaer 4165, calibrated) and amplified by a microphone amplifier (Brüel & Kjaer 2807). The microphone is placed in front of the guitar at a distance of 0,5 or 1 m from the plane formed by the strings, directly opposite the sound hole. The sound level is measured by a calibrated amplifier (Brüel & Kjaer 2636) or processed via the A/D converter. This dual channel A/D - D/A processor converts at a clock frequency up to 96 kHz at a depth of 24 bits (MOTU microbook I)

7. COMPUTER AIDED ANALYSIS

Today, A/D converters and home computers are well capable of running fast data acquisition systems, performing complex data conversion and analysis programs. Loudspeaker designers in particular have developed measuring procedures using MLS signals (Maximum Length Sequence) and sweep sine signals. The impulse response functions are recorded. By mathematical transformation the frequency response and many other functions can be obtained. The experiments can even be performed without using anechoic chambers.
Maximum Length Sequence (MLS) measuring procedures have a limited dynamic range and are sensitive to non-linearity in time and space. Therefore, sweep-sine signals are preferred. These signals are widely used in modern acoustic measurement analysis [19] – [21], [28] -[29]. The received impulse response function is processed by mathematical procedures called de-convolution. A higher level of excitation is possible, background noise is suppressed, and the immunity against harmonic distortion and time variance is excellent.
A number of software solutions were tested for this purpose, running either on a PC or on a MacBook Pro. The main objectives were to achieve consistent measurements, easy operation, and reliable and reproducible results. The systems under consideration were ARTA, SYSTune, FuzzMeasure, Baudline, Signal Scope Pro, WinMLS, Sample Champion PRO 3.8, Audio Tester V3.0, Data Physics SignalCalc, and a few others. For data presentation the systems ARTA (on a PC) and FuzzMeasure (on a MacBook) were used due to easy handling.

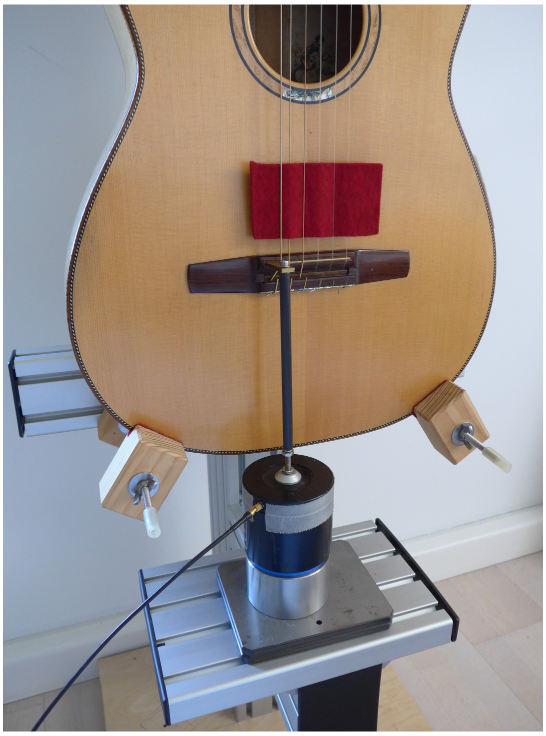

Fig. 1 Agitation of the guitar

8. ANECHOIC CHAMBER AND FEE FIELD MEASUREMENTS

A few measurements were performed in an anechoic chamber. This laboratory was available just a few days before it was demolished. Comparing these results with the measurements performed in the conventional laboratory room of 30 square meters, wall reflections and other acoustic characters did not deteriorate the measurements using sweep – sine signals. However, to be on the save side, acoustic panels where used to shield the test stand. Free-field measurements in the open air were only possible during late evening hours. The showed no significant deviation from laboratory results.

Fig. 2: Analogue measuring instruments

9 GENERAL CONSIDERATIONS ON THE FREQUENCY RESPONSE

The purpose of this test installation is the presentation of the guitar in the state as if played by the artist. The damping of the guitar due to the armrest and leg support is not simulated. The strings are tuned, so the soundboard is under normal tension. The strings are damped by a piece of felt. For all measurements the electric power to the shaker is kept constant within plus minus 1.5 dB, independent of frequency and time.

In order to familiarize with the test installation, simple resonance measurements were performed with the audio generator, amplifier, and shaker. More than 10 outstanding resonance peaks can be detected easily in the frequency range between 65 Hz (C) and 1000 Hz (b"). The resonance peaks are reproducible with an accuracy of less than 0,2% in amplitude and frequency.

Fig. 3 shows the typical frequency response of a sample guitar. It was obtained with a sweep sine signal from 40 Hz to 15.000 Hz in 10 seconds. The exciter was powered with 0,5 VA, resulting a maximum sound level pressure of 90 db.

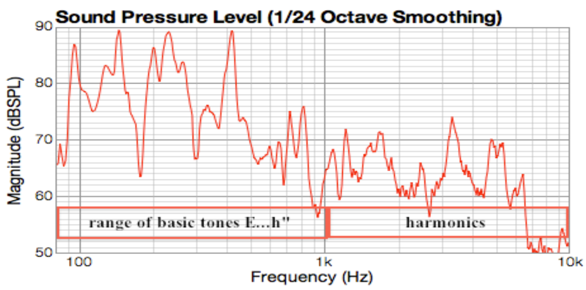

Fig.3: Frequency response of a guitar.

The microphone (Brüel & Kjaer ½ " type 4165) was places in front of the soundboard hole at a distance of 0,5 meters. Prominent resonance peaks are detected. At around 100 Hz we find the so-called Helmholtz resonance, depending on the volume of the guitar body and the size of the sound hole. The basic tones start at 82,4 Hz (E-string) and go up to 987 Hz (b", 19th fret). In this range we see deep drops followed by outstanding resonance peaks produced by modal oscillations of the soundboard and the bottom plate. From 1 kHz upwards the resonance peaks are still prominent, but do not reach the power of the lower range peaks. Deep valleys represent week energy radiation because of low efficiency at these frequencies. This frequency plot represents a "footprint" of the guitar under test.

10. THE FREQUENCY RANGES

Violins have been tested extensively in the attempt to classify their quality in terms of frequency response and acoustic performance [22]-[24], [33]-[36]. If we follow their analysis, the frequency range versus sound pressure level (SPL) is responsible for the performance of the instrument. The frequency ranges and their contribution to the sound are shown in Fig. 4.

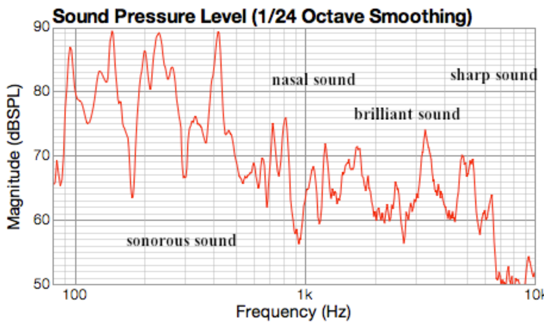

Fig. 4: Frequency ranges and their contribution to the sound character

At the lower end we have the Helmholtz resonance. Standard sized guitars resonate between E and G#. Up to 1000 Hz we find the basic tones of the guitar. The scale starts at E and ends at h" at the 18th fret of the fingerboard. The corresponding frequencies start at 82,4 Hz and reach to 988 Hz. We call this range the basic tones. High sound pressure levels in this range with not too deep valleys stand for a powerful, sonorous instrument.

Above 1kHz we see all the harmonics. They are responsible for the character of the instrument, its timbre, sweetness, modulation ability, clarity, even sustain.

Between 1,1 and 1,5 kHz the levels should not be too high, as the instruments tends to sound nasal and potty. With high sound pressure levels above 1,5 kHz the instrument sounds brilliant and penetrating. Around 1 kHz we find the formant "a", at 2 kHz the formant "e" and around 3 kHz the formant "i". The formats characterize a singer´s ability to fill the concert hall, even at high orchestra levels. If the guitar is strong in this frequency range, its tone is carried to the listener in the very last row of the hall.

11. DIRECTIONAL RADIATION OF SOUND

The guitar has no symmetry axis or plane. Therefore, it is obvious, that the sound perception of the listener depends very much on his position in reference to the guitar, at least at small distances. Different microphone position were chosen to show

this effect: the reference position is in front of the sound hole at a distance of 0,5 m. This position is compared to a 90-degree position in the virtual plane of the soundboard. This is approximately the position of the player's ear.

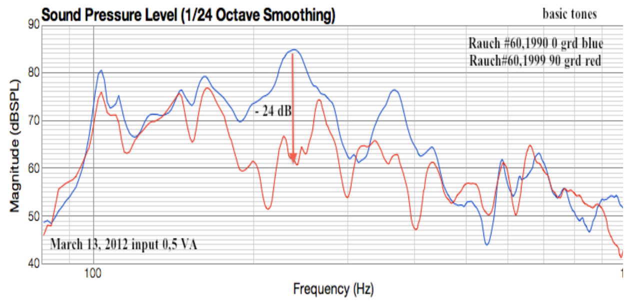

Fig.5: Sound pressure level near the artist´s hears (red) compared to the sound radiated perpendicular to the soundboard (blue)

12. THE INFLUENCE OF THE STRING TENSION ON THE SOUND PRODUCTION

A number of investigations on guitar frequency response report measurements without strings. The strings, when tuned to their nominal tension, impose a force of about 500 N to the soundboard. The soundboard acts as a membrane, agitated to different modal oscillations. These modes are influenced by the applied tension as shown in Fig. 6. Though the character remains, variations in frequency and volume are detected. The difference in the frequency response depends very much on the construction of the soundboard, e. g. stiffness and board thickness. All guitars are tested with strings under tension.

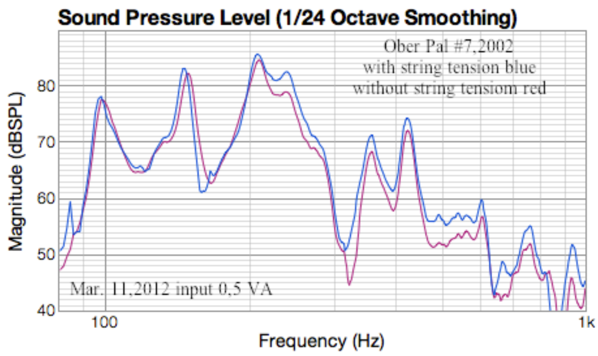

Fig. 6: Frequency response of the sample guitar with (red) and without (blue) sting tension.

13. HOW TO COMPARE GUITARS

All tests are performed using identical procedures. The shaker is driven with a constant power level of 0,5 VA plus minus 1,5 dB. For efficiency measurements, white noise signals and a single frequency of 1000 Hz are applied. As reference, a precision sound level meter (Brüel & Kjaer 2223) measures the emitted sound pressure level. A sweep sine signal is applied for the impulse transfer function response. The sweep time is 10 s for a frequency range from 40 Hz to15 kHz. A calibrated microphone (Brüel & Kjaer 4165) picks up the emitted signal. To verify the sound pressure levels calculated by the computer program, resonance peaks are verified by steady state measurements using a tone generator (Brüel & Kjaer 1049) and a measuring amplifier (Brüel & Kjaer 2436). These measurements do correspond with a deviation less than 0,5% in frequency and sound pressure level. The guitars under test are listed in the appendix.

14. PARAMETERS INFLUENCING THE SOUND

Above, we have discussed how direction determines the perception of the sound as well as the influence of sting tension on the sound production. There are, off course, many more parameters like temperature, humidity, positioning of the instrument (back plate damping) geometric parameters, mass distribution (machine head), age, and frequent usage of the instrument.

A few parameters have been examined within accessible limits. The impact of temperature is less prominent than expected. A 10 K difference causes less than 2 dB variations in SPL and less than 1% in frequency shift of resonance peaks. Off course, detuning of the strings by temperature is not considered, as their oscillations are excluded. Humidity variations up to 10 % rel. humidity are detectable by shift of peak frequency. Back plate damping was realized by sliding a foam panel between the structure pillar and the guitar back plate. No significant change was detected on the forward radiated sound.

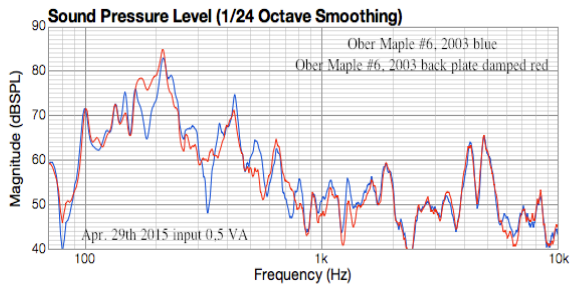

Fig. 7: Change of frequency response cause by back plate damping (red)

A chance in mass distribution was realized by fastening a mass of nearly 0,6 kg to the machine head of the guitar. Only very small changes in frequency response were detected at very high harmonics.

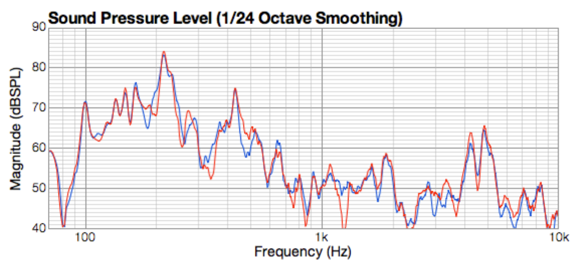

Fig. 8: Adding a mass of 0,6 kg to the machine head (red) has very little impact on the frequency response

Serious guitar artist is aware of the fact that his new guitar has to mature. The soundboard in particular will develop it´s full potential in colour and brightness with time and usage. This is demonstrated in Fig. 9. Not only the volume changes by more than 10 db in the basic tone range (below 1000 Hz), but also the

harmonics change significantly, presenting a different tone colour.

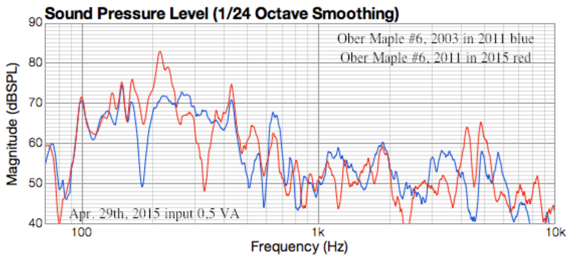

Fig 9: The guitar matures with time, blue: test in 2011, red: test in 2015

Historic instruments are sought after because of this maturing effect. Obviously, spruce rebuilds its cellular structure in such a way, that it is able to transform string oscillations into soundboard vibrations with a higher efficiency. This effect may well be achieved by a controlled heat treatment of the soundboard. The thermal modification process is similar to the aging process and is applied by a number of luthiers.

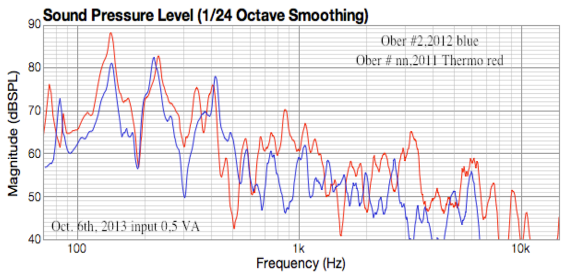

Fig. 10: Effect of thermal treatment of a spruce soundboard

New soundboard designs incorporate technologies developed in the aviation industries. The idea is to reduce the mass without decreasing stiffness and the ability to vibrate. Fig. 11 shows an example of a sandwich design. Although the character of the instrument does not change significantly, the sound pressure increases by a few db´s. Another welcoming effect is the quick response of the guitar, due to the low mass of the soundboard.

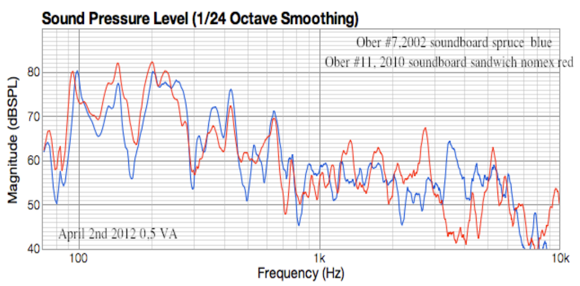

Fig. 11: Sandwich soundboard

On the other hand, many luthiers use historic instruments as an inspiring example to follow. So did Hermann Hauser I when he first saw, heard and measured a Torres guitar in the 30ies of last century. So do many followers today and offer “Hauser” models.
Ambitious artist even duplicate famous models to see if they can meet expectations and produce an instrument of equal sound pattern. Fig. 12 shows the frequency pattern of a H. Hauser II and the replica of the well known “La Leona” FE04 by Antonio Torres. This guitar is equipped with the tornavoz, a brass funnel, placed between the sound hole and the back plate. The effect can easily be recognized at 133 Hz, near C.

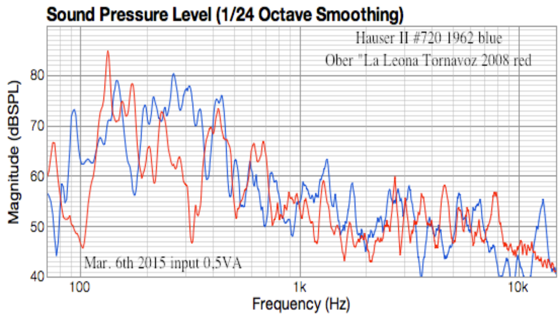

Fig. 12: Replica “La Leona” versus a H. Hauser II of 1962

15. CONLUSIONS

The frequency analysis is an excellent and easy to use tool to investigate and document the “footprint” of a guitar. Even small changes in size, weight, wood, and technology are detected. The method is simple and requires little investment. A lab-top computer is available everywhere, the software mentioned above is easy to handle and requires no programming skills. It should become a standard method to any luthier.

APPENDIX

Fritz Ober # 6, 2003, spruce, maple
Fritz Ober #7, 2002, spruce, rosewood
H. Hauser II #720, 1962, spruce, rosewood
H. Hauser I # ??, 1938, spruce, rosewood
H. Hauser I #??, 1935, spruce, rosewood
Guitarra Espaniola K04 MZ. #2004, spruce, side unknown
Fritz Ober # ??, 2010, spruce sandwich, rosewood
Armin Hanika Mod. 56 PF, 2009, spruce, Indian rosewood
Armin Hanika Mod 60PF, 2008, spruce, Indian rosewood
Otto Rauch #60, 1999, spruce, maple
Fritz Ober # 2010, spruce nomex, rosewood
Fritz Ober #?? 2011, thermo spruce, rosewood
Jose Garcia #??, 1912, spruce, rosewood
Santos Hernandez #??, 1925, spruce, rosewood
Manuel Ramierez #??, 1912, spruce, rosewood
Ulrike Meinel #2168, 1983 spruce, rosewood
Fritz Ober #5, 2012 sandwich thermo spruce/nomex, rosewood
Fritz Ober #nn 2012 sandwich thermo spruce/laser rosewood
Klaus Härtel #2013 spruce, rosewood
Fritz Ober #2, 2015 Copy “La Leona”, spruce, cypress
Fritz Ober #1, 2015 (Kasein) thermospruce, Rosewood

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